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Abstract

We investigate eruptive activity by analysis of thermal-alert data from the MODIS (Moderate Resolution Imaging Spectrometer) thermal infrared satellite instrument, detected by the MODVOLC (MODIS Volcano alert) algorithm. These data are openly available on a website, and easy to use. We show how such data can plug major gaps in the conventional monitoring record of volcanoes in an otherwise generally poorly-documented region (Melanesia), including: characterising the mechanism of lava effusion at Pago; demonstrating an earlier-than-realised onset of lava effusion at Lopevi; extending the known period of lava lake activity at Ambrym; and confirming on-going activity at Bagana, Langila and Tinakula. We also add to the record of activity even at some generally better-monitored volcanoes in Indonesia, but point out that care must be taken to recognise and exclude fires.

MODIS *remote sensing* *thermal monitoring* *Indonesia* *Melanesia*

MODIS, Moderate Resolution Imaging Spectrometer; MODVOLC, MODIS Volcano alert; NTI, normalised thermal index

Introduction

The MODIS (Moderate Resolution Imaging Spectrometer) Thermal Alerts website (http://modis.higp.hawaii.edu/), developed and maintained by the Hawaii Institute of Geophysics and Planetology's MODIS Thermal Alert Team (Flynn et al. 2002; Wright et al. 2002, 2004) hosts the first truly global high-temperature thermal monitoring system. This is capable of detecting and documenting changes in active lava flows, lava domes, lava lakes, strongly incandescent vents and hot pyroclastic flows. It has also been used to provide an estimate of the global vlcanic heat flux to the atmosphere (Wright and Flynn 2004).

Limitations to the utility of the system include: the external parts of ash clouds are not hot, and so ash clouds do not trigger thermal alerts; MODIS cannot see surface features through ash- or meteorologic-cloud (unless particularly thin and transparent); and the MODIS repeat frequency makes it liable to miss events of less than several hours duration. Volcanic features that are merely warm, such as crater-lakes and cooling (inactive) flows do not trigger alerts. Conversely, non-volcanic hot features such as fires *are* detected, so in some parts of the globe non-volcanic thermal alerts are common. Nevertheless, MODIS thermal alerts are capable of adding significantly to the record of activity of individual volcanoes, as we demonstrate below.

MODIS Thermal Alert data are openly and freely available at the website, providing a vast resource whose potential has barely begun to be exploited. It provides a global archive of daily thermal alerts beginning in August 2000, with few gaps (notably 16 June-1 July 2001 and 20-28 March 2002). The most recent data on the website are usually less than one day behind real-time.

As described by Flynn et al. (2002) and Wright et al. (2002, 2004), the MODIS Thermal Alerts website provides a series of maps updated every 24 hours to show ‘thermal alerts’ based originally only on infrared data from an instrument called MODIS that is carried by NASA’s Terra and Aqua satellites, launched in December 1999 and May 2002 respectively. Originally the website showed only night-time alerts (approximately 22.30 local time for Terra and 02.30 for Aqua), but now also shows day-time alerts (approximately 10.30 and 14.30 local time). Thermal alerts are calculated using the MODVOLC (MODIS Volcano alert) algorithm, which determines an ‘alert ratio’, otherwise known as the ‘Normalized

Thermal Index' or NTI, by calculating (4.0 µm radiance – 12 µm radiance)/(4.0 µm radiance + 12 µm radiance). MODVOLC triggers an alert on night-time data whenever this ratio has a value more positive than –0.800. This threshold value was chosen empirically by inspection of images containing known volcanic sites at high temperature (Wright et al. 2002), because it is the most negative value that avoids numerous false alarms in any region of the globe irrespective of local environmental conditions, such as background temperature. Using similar criteria for day-time data, and after corrrection for estimated solar reflection at 4.0 µm and geometric screening to eliminate sun-glint, the MODIS Thermal Alert Team have set a threshold of -0.600 (R. Wright, pers. comm. 2003; and http://modis.higp.hawaii.edu/daytime.html).

The MODIS nominal pixel-size is 1 km at nadir, but increases considerably towards the edge of the 2030 km wide imaging swath. Here the satellite zenith angle is nearly 60° with the result that each pixel represents an area of ground measuring 2.1 km in the along-track direction and 4.8 km in the across-track direction. However, the large swath width enables repeat night-time coverage from a single satellite to be achieved every 48 hours at the equator and at least daily at higher latitudes where orbital tracks converge. The frequency of coverage is doubled when day-time data are included.

Unfortunately, it is far from straightforward to specify how hot or large a feature must be in order to cause the pixel in which it lies to trigger a MODVOLC alert. This is because, in addition to the temperature of the hot feature, the radiances in each channel depend also on the hot feature's spatial dimensions, the temperature of ambient (or locally elevated) background, and the presence of any clouds of sub-pixel dimensions. However, by way of example, to yield a NTI more positive than –0.8 by night against ambient background temperatures of 0-30 °C, a hot surface at 400 °C would need to occupy more than about 0.07% of a pixel (700 m^2 for a pixel at nadir). However, a hot surface at 800 °C would only need to occupy more than about 0.01% of a pixel. To yield a NTI more positive than 0.0 a 400 °C hot surface would need to occupy more than about 2% of a pixel, but a 800 °C hot surface would only need to exceed about 0.2% of a pixel.

Figure 1

Here we demonstrate insights into volcanic activity gained using MODIS data for the period 1 January 2001- 31 March 2003 using Melanesia and selected parts of Indonesia as case studies (Figure 1), and use these to show the capabilities and limitations of such data for distinguishing types and patterns of activity. Previous remote sensing studies of this region have noted that cloud cover commonly hinders infrared (and visible) remote sensing, especially in the wet season (October-March in southern Indonesia), but that worthwhile time series can nevertheless be obtained (Carn and Oppenheimer 2000).

We have not had privileged access to MODVOLC data. The website makes them openly available to the scientific community, whom we encourage to take advantage of this opportunity to add to the documentation and analysis of volcanic activity from local, regional or global perspectives.

Data extraction from the MODIS Thermal Alerts website

Figure 2

Thermal alert maps can be called up on the website as daily, weekly, fortnightly, monthly, quarterly or annual compilations, covering user-selected areas of interest that can range from 0.5° 0.5° (50 km × 50 km) target areas around an individual volcano (Figure 2) up to the entire globe. These maps show 'hotspots' as green-yellow-red features according to the intensity of 4.0 μm radiance. This facilitates visual recognition of alerts, but to find out the exact co-ordinates of alert pixels the user must consult the 'text alert' file associated with each map. These files provide geographic co-ordinates of pixel centres, NTI values, radiances at 4.0 μm and 12 μm, and viewing geometry information for each alerted pixel.

We inspected monthly compilation maps to identify thermal alerts that coincide with volcanoes, and in most cases compiled records of alerts for each volcano by accepting all alert pixels within a 10 km box around each volcano's summit. The appendix outlines how we transferred the basic data from the website into spreadsheets that we used to generate the plots illustrated below. Here we describe the basis for our choice of plots.

Pixel content and choice of time-series plots

When wishing to use MODIS Thermal Alerts data to track or characterise volcanic activity, there is a choice of variables that can be displayed in a time series plot. The most obvious is simply the value of the NTI of each alerted pixel. To do so is undoubtedly useful (as we illustrate below), but some variation in NTI must reflect differences in viewing geometry between each overpass.

Figure 3

As described by Wright et al. (2002), the dwell time of the MODIS sensors is such that the thermal radiance from even a spatially very small hot source is likely to be shared between adjacent across-track pixels. A spatially small 'hot spot' will usually trigger an alert confined to a single-pixel only if the pixel falls centrally over it. In a shared case, the NTI of the two alerted pixels must always be lower than if the same alert had been concentrated into a single pixel. The exact relationship depends on the spatial dimensions and temperature of the 'hot spot' and the temperature of the background, but fortunately is not very sensitive to these. We calculate that an NTI of 0.0 for a point source anomaly centred in a single pixel would be reduced to about –0.27 if the same anomaly were shared equally between two adjacent pixels. This is an extreme case, because the effect is greatest for NTI values near zero. The difference reduces to about 0.04 for NTI of –0.8 and to between 0.1 and 0.2 (depending on 'hot spot' temperature) for NTI of +0.6 (Figure 3). In addition, if very close to the boundary between adjacent scan lines, a spatially small 'hot spot' could contribute radiance to all four pixels sharing a common corner.

Thus, even an alert consisting of up to two adjacent pixels in a single scan line or up to four pixels sharing a common corner could represent a spatially small source. If more pixels are affected, however, then the alert must denote a spatially extensive source, such as a lava flow more than a few hundred metres long. In such a case the time-varying number of alert pixels is capable of reflecting variations in spatial extent of an anomaly. We therefore choose also to plot the number of alert pixels at each volcano, and to interpret this plot in tandem with a simple NTI plot, bearing in mind that a decrease in NTI coincident with an increase in the number of alert pixels could be an artefact of changing viewing geometry of a source that has not necessarily changed.

Wright et al. (2002, 2004) point out that the across-track pixel overlap effects discussed above result in radiance being shared between pixels rather than being ‘double counted’. They therefore prefer to use the thermal alerts threshold merely as a filter to identify ‘hot’ pixels, and to plot the summed 4.0 μm radiance (after correction for solar radiance in day-time images) of alerted pixels for each volcano. We agree that this is useful, but point out that 4.0 μm radiance is more likely than NTI to be affected by variations in background temperature, whereas NTI, being a normalized difference ratio, contains a partial correction for this. Furthermore, summation fails to indicate the range and maximum magnitude of the anomaly within spatially extensive hot sources that genuinely extend across multiple pixels. Therefore, in our analysis below we generally present three time-series plots for each volcano: NTI of each alert pixel, number of alert pixels for each overpass, and summed (solar-corrected) 4.0 μm radiance for each volcano. In this study we generally show data only from the Terra satellite, but we include data from the Aqua satellite in our discussion of Pago and Langila volcanoes because their activity was wholly or mainly after the commencement of Aqua operations.

Geolocational accuracy and precision

The uncertainty in the true position of a point source that triggers a single-pixel thermal alert is necessarily about half a pixel (500 m at nadir), and there are other factors that compound this uncertainty. As described by Wright et al. (2004), MODVOLC pixel centre co-ordinates are referenced to the WGS-84 ellipsoid and corrected for parallax using the USGS GTOPO30 Digital Elevation Model, which has a resolution of 30 arcsec. Derived co-ordinates depend on the accuracy and precision of this model, and can be particularly in error off-nadir in areas of high topographic relief. However, Wright et al. (2002) report MODIS-derived volcano thermal alert locations generally within 1 km of their expected position, and Rothery et al. (2003) demonstrated errors of less than 1 km for known ‘point source’ industrial gas flares and other spatially small fires at or near sea-level in Britain and the North Sea.

In using MODVOLC thermal alerts data to document independently-verifiable volcanic activity, we have found that overlaying alert pixel centre co-ordinates on detailed maps of each volcano usually gives a reliable indication of the locus of activity and any migration therein. Our faith in MODVOLC geolocation received a boost when we noticed a recurrent thermal alert during 2002 at 29.64° N, 127.72° E, for which the only credible explanation was low-level activity at Suwanose-Jima in the Japanese Ryukyu Islands. However, the MODVOLC alert co-ordinates were about 10 km north of those that were currently shown for Suwanose-Jima in the Global Volcanism Program 'Volcanoes of the Word' catalogue (http://www.volcano.si.edu/gvp/world/index.cfm). This turned out to be a mistake inherited from the initial IAVCEI volcano catalogue entry for Japan (Kuno 1962) in which the latitude was quoted incorrectly (Lee Siebert, personal communication 2003). The discrepancy went unchallenged until MODVOLC study brought it to light, but the on-line catalogue co-ordinates have now been amended to show the correct summit location of 29.635° N, 127.716° E, based on a 1:25,000 Japanese topographic map. The active vent is in fact at 29.639° N, slightly to the north of the summit, so any error in the MODVOLC-derived position is considerably less than 1 km.

Volcanic activity in Melanesia January 2001 – March 2003

In order to establish the range of activity detectable by MODVOLC, we chose Melanesia as a test area. Some of the volcanic activity in this region is reported comprehensively enough to provide independent verification of our MODVOLC interpretations. However, many active volcanoes in Melanesia are uninstrumented and seldom visited by volcanologists. In such cases MODVOLC provides information on the timing and location of activity that is collected only by remote sensing and would otherwise go unrecorded.

Table 1

Wright et al. (2002) listed seven Melanesian volcanoes as sites of MODVOLC thermal alerts during the periods 1 October to 30 November 2000 and 1 February to 31 May 2001 (Ambrym, Bagana, Lopevi, Rabaul, Tinakula, Ulawun and Yasur). Our own MODVOLC survey of Melanesia for the whole of 2001 and 2002, reported initially in GVN (2003a), identifies the same seven plus Langila, Manam and Pago. Table 1 provides an overview, updated until 31 March 2003, and includes examples of every kind of volcanic activity capable of exposing incandescent material. We discuss each case below: first, three volcanoes (Pago, Rabaul and Ulawun) where there are ample independent data to corroborate the MODVOLC interpretation, then three (Lopevi, Manam and Yasur) where MODVOLC adds significantly to a body of independent information, and finally four (Ambrym, Bagana, Langila and Tinakula) where MODVOLC provides the main or sole reported evidence for activity during the period.

Pago (5.58º S, 150.52º E)

Pago is a young cone constructed within a 5.5 km × 7.5 km caldera. An eruption began on 3 August 2002 with a series of ash clouds followed within a few days by effusion of dacitic lava (much of it from new vents) that spread NW for 2-3 km until it became confined by the caldera wall (GVN 2002a, 2003b). This eruption began after Aqua became operational, and so we include Aqua data in our analysis.

Figure 4

For this example only we reproduce here some original MODIS imagery (Figure 4), not available from the MODVOLC website but downloadable from the Land Process Distributed Active Archive Centre at http://lpdaac.usgs.gov/main.asp. To examine images like this for every overpass would give information on meteorologic cloud cover, volcanic plumes and ash clouds, but such an approach would usually be impractical because of the data volume.

The first MODVOLC thermal alert during our reporting period was a single pixel in the 00:30 UT (10:30 local time) day-time overpass on 6 August 2002, for which the NTI was –0.31. The anomaly had increased to five pixels in size by the following night-time overpass 12:50 UT 6 August. One of these alert pixels had a NTI of –0.35, but the others were much closer to the detection threshold. This increase in the number of alert pixels over a twelve hour period could be mostly a pixel-sharing effect compounded by the satellite zenith angle being larger (38.7°) than in the day-time overpass (14.8°). Alternatively, it may indicate a dramatic expansion in the size of the hot area, which would be consistent with rapid initial growth of a new lava flow.

Figure 5

The MODIS Thermal Alerts website map for Pago on 6 August 2002 was shown in Figure 2, and Figure 5 shows our time-series plots (NTI, number of alert pixels and summed 4.0 µm radiance) for Pago throughout the entire eruption. The location of every alert pixel falls within the boundaries of the caldera and on or close to the known lava flow field (as illustrated in GVN 2003b), and the cause of each alert can confidently be attributed to active lava. The highest recorded NTI was –0.04 at 00:15 UT on 8 August (satellite zenith angle 15.0°). There were two alert pixels with almost equally high NTI (–0.08 and –0.13) at 00:25 UT on 15 August (satellite zenith angle 0.4°), when the summed 4.0 µm radiance reached its peak value of nearly 18 W m^{-2} sr^{-1} μm^{-1}.

Subsequently, all three signals share a declining trend until the final thermal alert on 15 January 2003. There is a substantial body of work (examined by Wright et al. 2001) that has shown how remotely-sensed infrared flux from active lava flows correlates with the current size of the most active area of the flow and hence with eruption rate. It is thus reasonable to treat the upper boundary of the NTI envelope and the trend of the summed 4.0 µm radiance as proxies to track the eruption rate at Pago. The crudely exponential decline shown by these is consistent with eruption from a pressurised system (a Type I effusive eruption of Harris et al. 2000), which in this case would be the NW-SE fissure system from which the lava was erupted (GVN 2002b), rather than being indicative of the long-term magma supply rate to the volcano. This is an important inference about the nature of this particular eruption, which, to the best of our knowledge, has not hitherto been made.

Rabaul (4.271º S, 152.203º E)

The Tavurvur cone on the eastern rim of Rabaul caldera has been a site of frequent vulcanian and strombolian ash emission and occasional night-time incandescence ever since a 51 year interval of repose ended on 19 September 1994 (GVN 1994, Williams 1995). During our analysis period, activity has been of an intensity likely to fall close to the MODVOLC detection threshold. Explosive events can cause the thermal radiance from a vent to vary severalfold or even by orders of magnitude on timescales of minutes to hours. Therefore, the instantaneous signal detected from eruptive centres like Tavurvur during any individual MODIS overpass is not necessarily representative of the average state, and alert-free intervals of up to several months do not necessarily demonstrate an overall decline in activity.

Figure 6

Figure 6 shows common, but by no means ubiquitous, thermal alerts at Rabaul during our study period. The onset of thermal alerts (26 April 2001) can be related to a change in activity from occasional sub-continuous ash emission to frequent, short-duration ash cloud expulsion that occurred at about 14:00 on 25 April (GVN 2001a). However, we are aware of no particular event to explain the highest (most positive) NTI, which was –0.263 on 4 July (12:45 UT) when summed 4 μm radiance also attained its highest value for the entire period. Rabaul Volcano Observatory reports (GVN 2001b) document a relatively quiet interval characterised by emission of thin, white vapour from 20 June until 28 August, but possibly our extreme anomaly captured the initial onset of a minor explosion when radiance would have briefly peaked. The only two-pixel alert subsequent to this was 22 October 2002, which may represent the aftermath of a large explosion documented on 20 October (GVN 2002c).

Alert-pixel cetnres form a tight 1 km^2 cluster, but as mapped are systematically displaced by about 1 km to the west of Tavurvur (which places some of them in the sea!). In most instances the alert is likely to have been triggered by thermal radiance from the hot vent, and there can be no doubt that the alerts all correspond to Tavurvur rather than another volcanic centre or other likely thermal source. Any real migration in the vent location would surely have been reported at this volcano, so it is likely that there is a mismatch between the base map and the WGS-84 ellipsoid used in MODIS geolocation.

Ulawun (5.05º S, 151.33º E)

Ulawun is a 2334 m high stratocone volcano, characterised in recent years by mild but variable seismic activity and low-level ash plumes. The only MODVOLC thermal alerts during our reporting period were for the three night-time overpasses on 26, 27 and 28 April 2001 that were recorded between 12:15 and 13:10 UT. The highest NTI on each occasion was between about –0.2 and 0.0, and the summed 4.0 µm spectral radiance was highest on the third day, when there were 15 alert pixels. Alert pixel centres were clustered around the summit on all three days, with few outliers more than 3 km away. These are clearly a response to Ulawun's 25-30 April 2001 eruption (GVN 2001c), which included strombolian eruptions (from 05:30 local time on 26 April, which is 19:30 UT 25 April). Activity is described as particularly intense between local times 05:30 27 April and 11:30 28 April (19:30 UT 26 April; 01:30 UT 28 April), when incandescent material rolled almost a third of the way down the slopes and a lava flow several km in length reached the 600 m contour. The MODVOLC data for 28 April suggest that effusion of fresh material was continuing at least until 12:15 UT (22:15 local time), which is the time of the latest thermal alert.

We note that MODVOLC did not detect any thermal alerts associated with the only other significant eruptions on record during the reporting period, which produced low-level ash clouds in late August-early September 2002 (GVN 2002e) that would not in themselves be expected to be detected by MODVOLC.

Lopevi (16.507º S, 168.346º E)

Lopevi, an island stratocone with a summit elevation of 1413 m, is one of Vanuatu's most active volcanoes. The only independently-reported activity during our reporting period is an explosive eruption beginning 8 June 2001 that continued until at least 19 June (GVN 2001d). According to those reports, an a'a flow spread from a vent on the western flank vent on 8 June, and two flows from a source nearer the summit were believed by a local guide to have been emplaced on 15 June (GVN 2001d).

Throughout our entire 27 month reporting period the only MODIS thermal alerts at Lopevi were three pixels at 11:10 UT on 9 June 2001 with a maximum NTI of –0.30 and two pixels at 11:25 UT on 14 June, both with an extremely high NTI of about +0.33. On the first date the alert-pixel locations plot low on the western flank whereas on the second date they plot closer to the summit. These data provide striking corroboration of the events already reported, but show that emplacement of the supposed 15 June flows had already begun by the time of our second MODIS alert, which corresponds to 22:25 local time 14 June.

Manam (4.10º S, 145.061º E)

Figure 7

Manam is a 1807 m stratocone forming a 10 km wide island off the northern coast of Papua New Guinea, and is one of the country's most active volcanoes (Palfreyman and Cooke 1976). Frequent explosions were heard through cloud in March 2002 with a 'moderate sized' strombolian eruption at 05:00 local time on 20 May 2002 (GVN 2002d), which is 19:00 UT 19 May. A seismograph was installed on 22 May and recorded moderate seismicity 22-24 May, which declined over the following week (GVN 2003c). MODVOLC thermal alerts during our reporting period occurred only between 7 April and 21 May (Figure 7). All three parameters peaked in the 00:15 UT day-time overpass of 20 May, which is 10:15 local time. The apparently large spatial extent of the thermal anomaly at this time (10 pixels) is probably partly (but not wholly) an artefact of being imaged close to the swath edge at satellite zenith angle of 53.5°. The alert had reduced to 7 pixels in size by the time of the following night-time overpass (12:35 UT), when the satellite zenith angle was 32.2°, and both the NTI and summed 4.0 μm radiance had fallen too. On the following day there remained only a single alert-pixel. The short duration, rapid decline, and spatial distribution of alert-pixel centres associated with this event are consistent with a hot avalanche channelled down a known valley extending northwest from the summit. This would also seem to be the main focus of previous thermal alerts.

In this instance, MODVOLC unquestionably detected the immediate aftermath of the 20 May (local time) explosion. In addition, it provides the only reported evidence for similar, but lesser, activity earlier in the month.

Yasur (19.52º S, 169.425º E)

Figure 8

Yasur is a 361 m pyroclastic cone at the SE tip of Tanna island (Vanuatu), and has exhibited continual strombolian and vulcanian activity since at least the time of Captain Cook's visit in 1774 (Cook 1999). Our MODVOLC thermal alert survey (Figure 8) shows only three alerts during 2001, with NTIs scarcely greater than -0.8. This is consistent with minor fluctuations above a background level of activity whose thermal signal was usually below the MODVOLC detection threshold. Alerts became more frequent and stronger from 31 January 2002, and were especially common and strong in the two months beginning 29 August 2002, following the 29 August 2002 M6 volcanic earthquake, which was the strongest felt at Yasur in living memory (GVN 2003d). Ground-based reports for August-December 2002 (GVN op. cit.) note strombolian eruptions from up to three vents in the active crater.

In this instance MODVOLC detected incandescent vents and/or strombolian explosions, and recoorded the intensification of activity in the latter third of 2002. Alert-pixel centres plot tightly in a cluster about 1.5 km east-south-east of the mapped location of the crater (GVN 1999). There is evidently no new vent in this location, and the discrepancy almost certainly reflects a mismatch or error in co-ordinate systems.

Ambrym (16.25º S, 168.12º E)

Ambrym is one of the most active volcanoes of the New Hebrides (Vanuatu) arc, but despite on-going activity since June 1996, reported observations have been intermittent. It is a basaltic pyroclastic shield, with two active cones named Benbow and Marum (Robin et al. 1993). The most recent reported observations before our reporting period record degassing lava lakes in craters on both cones in August-September 2000 (GVN 2001e). Subsequent reports suggest two small lava lakes appearing in Mbwelesu crater (a satellite of the main Marum crater) during February 2001, ‘reappearance’ of Benbow lava lake during June 2002 and active lava lakes at both Benbow and Merum/Mbwelesu in November-December 2002 (GVN 2002f).

Figure 9

Figure 10

Our MODVOLC survey shows continual thermal alerts from 10 March 2001 until the end of our reporting period, the spatial distribution of which defines two discrete clusters that we interpret to be the two lava lake sites (Figure 9). Figure 10 shows our time-series plots, in which we distinguish alerts to show to which of the two spatial clusters each one belongs. This shows that both centres were continually active from 10 March 2001 (Benbow) and 9 April 2001

(Marum/Mbwelesu), providing strong evidence for persistence of the lava lakes and for the ability of MODVOLC to detect these. Sporadic high NTI values for both centres during this period are most simply interpreted as satellite overpasses coincident with lava lake overturning episodes.

Bagana (6.140º S, 155.195º E)

Bagana is a 1750 m symmetrical lava cone in a remote part of Bougainville Island (Papua New Guinea). Activity is assumed to be on-going and characterised by effusion of an andesitic lava dome that gives birth to occasional lava and pyroclastic flows (Bultitude 1976). However, as a consequence of civil unrest, the most recent known reports other than our MODVOLC survey date from 1991 and 1995, (GVN 1995, 2003e).

Figure 11

Our survey shows continual thermal alerts throughout the entire reporting period (Figure 11), and we propose this as the first independent evidence that lava dome activity at Bagana has continued into the new millenium. Alert-pixels are generally clustered around the summit, with the notable exception of a 5-pixel alert on 21 November 2002 which includes a line of four pixels extending towards the eastern foot of the edifice. This includes the highest NTI (-0.51) and the highest total 4.0 μm radiance radiance for the entire period. The latter suggests that size of the anomaly is not simply a viewing-angle effect, and instead is likely to represent either an active lava flow of relatively short duration or a freshly-emplaced hot pyroclastic flow.

Langila (5.525º S, 148.42º E)

Langila consists of four overlapping composite cones on the flank of the extinct Talawe volcano in NW New Britain. The past thirty years have been marked by frequent strombolian or vulcanian eruptions. The most recent ground-based report notes mild vulcanian activity June-October 2000 (GVN 2000), none of which was detected by MODVOLC. During our reporting period, MODVOLC detected alerts at Langila only between 25 May 2002 and 13 October 2002.

Figure 12

To test whether we could detect a thermal anomaly on other dates, in this case we made a search of all locally cloud-free Terra MODIS imagery from 1 May to 31 October 2002. We found thermally anomalous pixels with NTI below the –0.800 MODVOLC threshold on 25 dates extending from 20 May until 25 October 2002. These points are included in Figure 12.

Alerts were particularly intense during August. With the exception of an outlying pixel in a 3-pixel alert on 14 August when the satellite zenith angle was a fairly extreme 62.7°, all fall within about 1 km of the position of the active craters, and are consistent with an active dome or incandescent vent. The only independent evidence that we know of for activity at Langila is a Darwin Volcanic Ash Advisory Center report of an ash cloud rising to about 3.4 km on 11 July 2002, based on a pilot report (GVN 2003f). However, this very tight clustering of alert pixel centres and the persistence of alerts throughout a five-month period convinces us that the cause is otherwise-unreported volcanic activity, rather than the dry-season bush fires discussed below for several Indonesian examples.

Tinakula (10.38º S, 165.80º E)

Tinakula (Solomon Islands) is a stratocone island similar to Stromboli rising to 851 m above sea-level, which has been uninhabited since a tsunami in 1971. Expert reports have been very scarce for the past thirty years, with none to the Global Volcanism Program since 1985 (GVN 1985a). However casual reports (GVN 2003g) confirm on-going ash emission for the periods August 1989-February 1990, September 1995, May 1999 and less specific activity in March-April and November 2002. During our reporting period, MODVOLC thermal alerts occurred only in 2001 on 15 January (one pixel), 6 March (one pixel) and 16 April (two pixels). Each was only slightly above the detection threshold, with the highest NTI being -0.75 on 6 March. Each alert pixel was within 1 km of the summit.

A labour-intensive search of Terra MODIS day- and night-time data located additional images on which Tinakula was free of cloud only during January-April 2001, August-September 2001, January 2002 and August-September 2002. There was a recognisable thermal anomaly on only two of these: by night on 10 January (NTI –0.804) and by day on 25 January (NTI –0.790). We conclude that Tinakula may have experienced sustained mild strombolian-vulcanian activity throughout our study period, but that the thermal signal rose close to the MODVOLC detection threshold only during January-April 2001. Cloud prevents corroboration by MODIS of the independently-reported activity in March-April and November 2002.

Volcanic activity and non-volcanic alerts in Indonesia 2001-2003

As is well known, MODIS is also capable of detecting fires (Justice et al. 2002). Detection of emission in the 4 μm and 12 μm wavebands alone provides no basis for distinguishing between fires and hot volcanic features, so at sites of sufficiently large fires the MODVOLC algorithm triggers thermal alerts that can be distinguished from volcanic alerts only on the basis of context (Flynn et al. 2002, Rothery et al. 2003).

Figure 13

Generally speaking, volcanic thermal alerts can be expected to be concentrated around volcano summits or known secondary vents, with a more linear distribution in the case of sufficiently long hot flows. Contextual considerations, and in some cases persistence, make it unlikely that many of the Melanesian thermal-alerts discussed above are actually fires rather than hot volcanic phenomena. However, in a survey of Java and Bali over the same period we found several examples of fires that could easily be mistaken for eruptions. In particular, the period August-October 2002 saw numerous examples of what we interpret as non-volcanic thermal alerts on several volcanoes in east-central Java (Figure 13), whose upper slopes are more densely vegetated than the lower-lying surroundings. In most cases few or no alerts occurred at these sites throughout the rest of our reporting period. July, August and September are usually the driest three months in eastern Java (e.g., Hendon 2003), and it seems that bush fires were particularly prevalent in August-October 2002. This dry season evidently saw the worst fires since the 1997 drought that was associated with the 1997/8 El Nino-Southern Oscillation event (Kirono et al. 1999, Wooster and Strub 2002). In a 23 month study using 4 km pixel-size Advanced Very High Resolution Radiometer thermal satellite images of Indonesian volcanoes in 1996-7, Carn and

Oppenheimer (2000) also recognised several thermal anomalies caused by bush fires.

Table 2

We document some of our non-volcanic alerts below, and comment on how thoughtful analysis can help to distinguish between volcanic and non-volcanic alerts. MODVOLC did detect genuine (though already sufficiently well-known) activity at some Javanese volcanoes. Table 2 provides a summary.

Non-volcanic alerts on Java and Bali

Lawu (7.625º S, 111.192º E) and Wilis (7.808º S, 111.758 ºE)

Figure 14

Figure 15

Lawu is a Holocene complex with no historical eruptive activity, although there are fumaroles on the south flank. Lawu shows a series of MODVOLC thermal alerts in October 2002 (Figure 14), but an eruption on Java of the size implied by the NTI and number of alert pixels would certainly have been reported. We are therefore confident that this is a false alarm, caused by bush fires. We interpret the alert-pixel distribution (Figure 15) as indicating bush fires that migrated across the north side of the summit 10-12 October and across the south side of the summit 19-24 October. Similarly Wilis, which lies 30 km east of Lawu, has no confirmed historical eruptions, and having consulted with colleagues in the Volcano Survey of Indonesia (Dali Ahmad and Rudy Dalimin, personal communication 2004) we are confident that the August-October thermal alerts on Wilis were caused by fires.

Arjuno-Welirang (7.725º S, 112.58º E)

Arjuno and Welirang are opposite ends of a 6 km long overlapping stratocone complex in eastern Java. There has been no confirmed eruptive activity here since the 1950s. Space Shuttle astronauts photographed plumes extending from the summit in 1991 (GVN 1991) and 1994, which were not necessarily volcanic and could be fire smoke or meteorologic phenomena. During our reporting period, MODVOLC detected thermal alerts at Arjuno-Welirang on seven dates from 13 August to 24 October 2002. A local seismometer detected nothing more than a few distant tectonic earthquakes at this time (Dali Ahmad, personal communication 2003), so we believe that the thermal alerts were triggered by fires rather than having a volcanic origin. A clue that this was the case comes from the spatial distribution of the alert-pixels, the locus of which changes from day to day in a manner consistent with fires migrating across the the complex.

Kawi-Butak (7.92º S, 112.45º E)

Kawi-Butak is a stratocone lying south of Arjuno-Weliran and east of Kelut volcano. It has no known historical eruptions, but MODVOLC reveals thermal alerts scattered around the summit of this volcano in August and October 2002 (Table 2). The alert-pixels on 12 October have the correct spatial distribution to be a northward flowing lava flow originating at the summit. However, by the following day no alert-pixels remained here, although there was one several km to the south. No eruption of any kind has been reported here, and the volcano was very quiet seismically (Dali Ahmad, personal communication 2003), so we attribute these alerts to a family of short-lived bush fires.

Lamongan (8.00º S, 113.342º E)

Lamongan (Carn 2000) is a stratocone east of the area covered by Figure 12 (Figure 1). The most recent eruptions were during the 19th century, although it remains seismically active (GVN 1985b). Thermal alerts occurred as single pixels on three dates during the 2001 dry season and as multiple pixels on numerous dates during the 2002 dry season (Table 2). A cluster of alert pixels at the summit on 1, 3 and 5 September 2002 is particularly noteworthy, but there can be little doubt that the alerts represent fires in every case.

Ijen (8.058º S, 114.242º E)

The Ijen volcano complex near the eastern end of Java (Figure 1) consists of a group of small stratocones within the 20 km-wide Ijen caldera. The only known present day eruptive location within the complex is Kawa Ijen, well-known as a site of manual sulfur mining. Eruptions here would surely have been reported, but the published record for our reporting period is limited to small explosions (mostly in 2001) and elevated volcano seismicity since October 2001 (GVN 2001f, g, 2002g,h,i).

Figure 16

MODVOLC detected a considerable number of thermal alerts in and around Ijen caldera, mostly August-September 2001 and September-October 2002 (Figure 16). Many of these were on the caldera floor (where there are many coffee plantations), and can be reasonably interpreted only as fires. Others occur closer to Kawa Ijen, including a day-time thermal alert with a NTI of +0.568 within 2 km of the Kawa Ijen crater at 02:45 UT (09:45 local time) on 19 October 2002. This NTI is considerably higher than any value we found in Melanesia and is comparable to the values seen during major lava effusion at Nyiragongo (GVN 2002p). We would have strongly suspected short-lived lava effusion at Kawa Ijen at this time, if this volcano were not so comprehensively documented on the ground. In fact, this 19 October thermal alert corresponds to a fire that destroyed at least one Volcanological Survey of Indonesia seismometer (Dali Ahmad, personal communication 2003).

Agung (8.342º S, 115.508º E)

During our reporting period MODVOLC thermal alerts occurred on the Balinese volcano Agung (Figure 1), once in the 2001 dry season and twice in the 2002 dry season (Table 2). On the first two occasions the alert was two pixels in size, and about 2 km NNE of the summit, and on the final occasion the alert was a single pixel 1 km SE of the summit. Eruptions here would not have gone unreported, and so we interpret these thermal alerts as fires.

Genuine volcanic thermal alerts in Java

In contrast to the non-volcanic alerts reported above, there are three Javanese volcanoes where MODVOLC detected thermal alerts of unquestionable volcanic origin during our reporting period: Semeru, Merapi and Karakatau.

Semeru (8.108º S, 112.92º E)

Figure 17

Semeru (Figure 13) is a stratocone that has been in almost continuous eruption since 1967, characterised in recent years by explosions in the summit crater that produce ash plumes and pyroclastic flows. There were thermal alerts at Semeru throughout our entire reporting period (Figure 17), but they increased in frequency and intensity from April 2002 onwards. This corresponds fairly well with the onset of a time of enhanced explosive activity with attendant avalanches and pyroclastic flows in March (GVN 2002j). Analysis of the spatial distribution of the alert pixels shows them tightly clustered on the south side of the summit, which is the location of most avalanches and pyroclastic flows, but by analogy with previously discussed examples it is possible that some of the alert pixels in August-October 2002 are a result of fires.

Merapi (7.752º S, 110.442º E)

Figure 18

Merapi is a highly active stratocone in central Java (Figure 1), in this case with an active lava dome that frequently sheds hot pyroclastic flows down the W and S flanks for distances of 2-5 km (Siswowidjoyo et al. 1995). During our reporting period, MODVOLC thermal alerts occurred from late January 2001 until mid January 2002 (Figure 18), which is a period marked by frequent dome collapse and hot avalanches (GVN 2001h,i,j, 2002k). There were no further alerts except for four dates between late March and late May 2002, when there was a temporary renewal of pyroclastic flow activity prior to a quieter (but not pyroclastic flow-free) second half to the year (GVN 2002l). Significicantly there were no alerts during the 2002 dry season. The spatial distribution of the alert pixels shows a tight grouping around the summit as expected if the cause is mostly a hot lava dome.

The thermal alerts for Semeru and Merapi prove that MODVOLC can detect activity at volcanoes characterised by pyroclastic flows. They do not offer any obvious basis for distinguishing between a hot vent with explosion-fed pyroclastic flows (Semeru) and a hot dome with dome collapse-fed pyroclastic flows (Merapi), but are sufficient to increase confidence in our interpretation of on-going lava dome activity at Bagana, which appears similar except that we have not seen such high NTI or total 4.0 μm radiance there.

Krakatau (6.102º S, 105.423º E)

The only other Javanese volcano with MODVOLC thermal alerts during our reporting period is Krakatau (Figure 1) where alerts occurred only between 31 July and 17 September 2001. Based on GVN reports, we relate these alerts to temporarily elevated activity characterised by ash and bomb emission during August 2001 and a higher than usual number of explosions and volcanic earthquakes in early September (GVN 2001k).

Comparisons

We close by considering how much volcanological information could be gained about any newly active or previously unstudied volcano by means of MODVOLC. The form of the MODVOLC signals for Pago in Figure 4 is similar to that from lava effusion eruptions of Nyamuragira in 2002 (GVN 2003g) and Stromboli in 2003 (GVN 2003h) and we propose that a crudely exponential decline of the NTI envelope, preferably supported by a similar decline in summed 4.0 μm radiance, is a general characteristic by which Type I lava effusion can be distinguished using MODVOLC data.

In contrast, our study provides only a weak basis for distinguishing between lava lakes and lava domes using MODVOLC data alone, because both are characterised by persistent (but time-variable) thermal-alerts concentrated at discrete locations. It might be possible to glean further insights through statistical time-series analyses, but this would be greatly complicated by such factors as the inherently different cloud- and fire-situations at each volcano, and the differing spatial dimensions of local thermal sources. Fortunately, even rudimentary knowledge about a volcano's chemistry or history would almost always provide sufficient context to avoid confusing a lava dome with a lava lake. Moreover, no volcano with a lava dome is likely to yield magma of sufficiently low viscosity to generate a rapidly-emplaced lava flow, so any site of persistent thermal alerts associated with outbursts of 4.0 μm total radiance total exceeding 100 W m^{-2} sr^{-1} μm^{-1} and occupying tens of pixels as in the case of Nyiragongo January 2002 (GVN 2003i) is likely to be a lava lake. A pyroclastic flow from a lava dome might appear similar for the first few hours but it would cease to generate thermal alerts within days if not within hours.

Conclusions

We caution against attempts to over-analyse MODVOLC data. They are only a crude record, at low spatial resolution, of phenomena whose signatures may depend considerably upon spatial resolution (e.g. Gaonac'h et al. 2003). Data points are restricted to those whose NTI exceeds the globaly-set threshold so that inevitably there is some latitudinal, altitudinal and seasonal variation within and between MODVOLC records for each volcano.

Nevertheless, the MODIS Thermal Alerts Website makes available valuable thermal data covering all the world's sub-aerial volcanoes. The most recent data are commonly only about 24 hours old, and offer a first-order tool for the characterisation of new activity. Consideration of NTI, total 4 μm radiance, and the spatial distribution of alert-pixels makes most active lava flows readily identifiable, and time-series data offer insights into the eruptive mechanism. Active lava lakes, lava domes and incandescent explosive vents can all be detected, and distinguished if rudimentary contextual information is available. The location of any thermal alert caused by fires near a volcano summit tends to be more spatially variable than that of any genuine volcanic thermal alert.

MODVOLC data are simple to use, and are accumulating into a several-year-long archive whose potential has barely begun to be tapped. We have shown examples where MODVOLC data are the main or sole documentary evidence for a volcano's activity (most notably Ambrym, Bagana, and Langila) and others (such as Pago and Lopevi) where MODIS data allow confirmation or refinement of the timing and nature of independently documented events.

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Appendix: transfer of MODVOLC data from website to spreadsheets and further processing

We extracted MODVOLC data for each target volcano from the MODIS website (http://modis.higp.hawaii.edu/). By using the option *Summarize by month* and then downloading the related *Text alert file* (.txt format) we obtained the data for one entire month are displayed in rows. Each row contains the information for a single alert pixel. The information consists of the time of satellite's overpass, latitude and longitude of the centre of the alert-pixel, detected radiance in five MODIS channels, satellite zenith angle and azimuth relative to the alert-pixel cent, solar zenith angle at the alert-pixel centre, and the value of alert ratio.

By saving the *Text alert file* in an Excel spreadsheet we were able to order and analyze the data by column. Sorting by latitude and longitude in turn made it convenient for us to delete all the alert-pixels falling beyond the area of interest (usually a 10 km box around the summit). We then added each month's spatially-filtered data to a master spreadsheet for the volcano, containing all that volcano's alerts for the entire reporting period. From this we generated three different worksheets: one for analysis of the NTI or alert ratio (*ratio*), one for the number of alert pixels (*n_alert*), and one for the total 4.0 μm spectral radiance (*radiance*). The time-series graphs presented in this paper were generated from these.

In the case of day-time data, the 4.0 μm thermal signal is always contaminated by reflected sunlight, so we applied the same empirical correction used by the MODIS team to generate day-time NTI (R. Wright, pers. comm. 2003). We identified as day-time all those data acquisitions for which solar zenith angle was <90°and for these we made a solar correction to the MODIS band 21 (4.0 μm) spectral radiance by subtracting from it 4.26% of the MODIS band 6 (1.6 μm) spectral radiance.

In the *ratio* worksheet, we ordered the data by date and time (for this we generated an extra data column, called *date-time*, containing year, month, day, hour, minute of the satellite's overpass) and we plotted the value of alert ratio versus date-time in a graph covering all the monitored period.

To analyse the number of alert pixels and the total spectral radiance recorded by each satellite overpass, it was necessary to distinguish groups of pixels sharing the same date and time (date would be insufficient at high latitudes, where there may be data from several overpasses on a single date). We achieved this using a function of Excel called "subtotals" (Menu Bar – Data). For each change in the column *date-time*, we used the formula "count the cells with the same value in the date-time column" (to count the number of pixels) and "sum the value of 4.0 μm radiance of the cells with the same value in *date-time* column" (to calculate the total spectral radiance at 4.0 μm). We thus obtained for each satellite overpass the number of alert pixels and the total (solar corrected) spectral radiance at 4.0 μm.

We used the latitudes and longitudes of alert-pixel centres in the spreadsheets to plot the spatial distribution of alerts, which we used as overlays on maps of each volcano.

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GVN (2001c) Ulawun. Bulletin of the Global Volcanism Network 26(6): 5-7
GVN (2001d) Lopevi. Bulletin of the Global Volcanism Network 26(8): 2-4
GVN (2001e) Ambrym. Bulletin of the Global Volcanism Network 26(2): 4-5
GVN (2001f) Ijen. Bulletin of the Global Volcanism Network 26(9): 5-6
GVN (2001g) Ijen. Bulletin of the Global Volcanism Network 26(12): 9
GVN (2001h) Merapi. Bulletin of the Global Volcanism Network 26(1): 2-3
GVN (2001i) Merapi. Bulletin of the Global Volcanism Network 26(7): 9-10
GVN (2001j) Merapi. Bulletin of the Global Volcanism Network 26(10): 4-6
GVN (2001k) Krakatau. Bulletin of the Global Volcanism Network 26(9): 5
GVN (2002a) Pago. Bulletin of the Global Volcanism Network 27(7): 5-6
GVN (2002b) Pago. Bulletin of the Global Volcanism Network 27(8): 2-3
GVN (2002c) Rabaul. Bulletin of the Global Volcanism Network 27(11): 7-8
GVN (2002d) Manam. Bulletin of the Global Volcanism Network 27(5): 7
GVN (2002e) Ulawun. Bulletin of the Global Volcanism Network 27(8): 3-4
GVN (2002f) Ambrym. Bulletin of the Global Volcanism Network 27(12): 2-4
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Figures

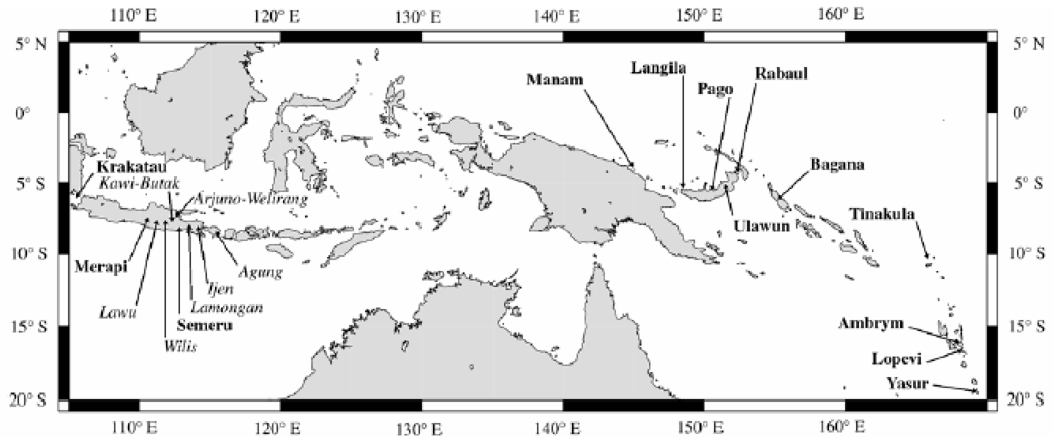

Figure 1 Map showing the locations of Melanesian and Indonesian MODVOLC thermal alerts described in the text. The volcano names in italic script are sites of thermal alerts attributed to fires rather than eruptive activity.

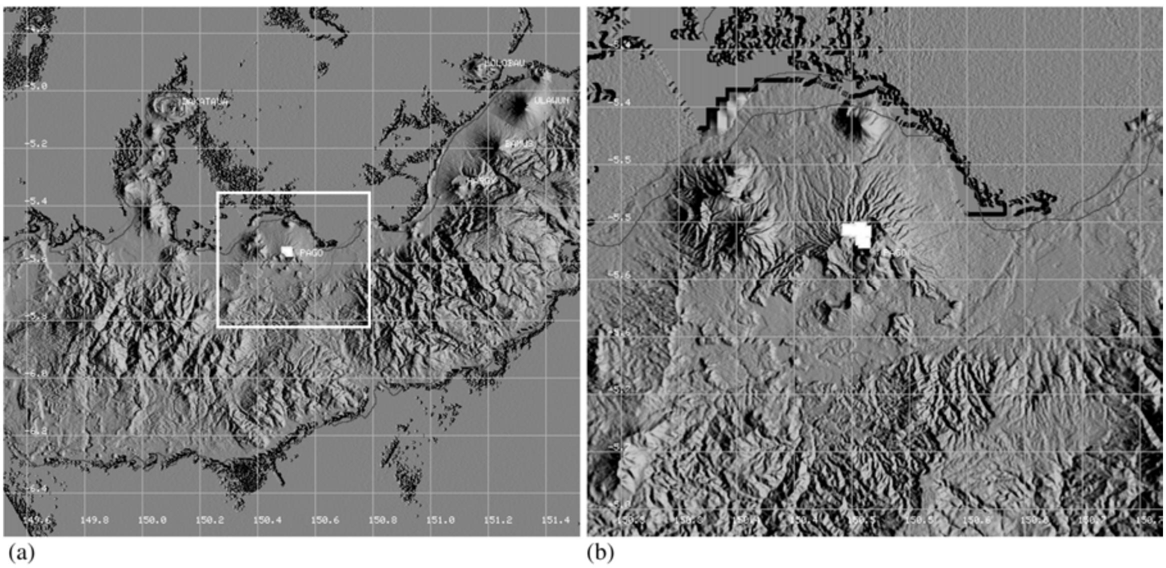

Figure 2 MODVOLC thermal alerts for 15 August 2002, taken from the MODIS Thermal Alerts website. (a) 2° square centred on Pago (gridlines every 0.2°, approx. 20 km), superimposed box identifies the area shown in (b), (b) 0.5° square centred on Pago (gridlines every 0.05°, approx. 5 km). Each consists of a topographic base with alert pixels superimposed. The alert pixels are the cluster of six overlapping white squares close to the centre of each view, and are displayed in colour on the website. In this example the alert pixels correspond to known intra-caldera lava effusion, which is discussed in the text. Exact centre co-ordinates of each alert pixel are provided in text files accessible at the website, which in this case also reveals that three of the alert pixels were detected by day and three by night.

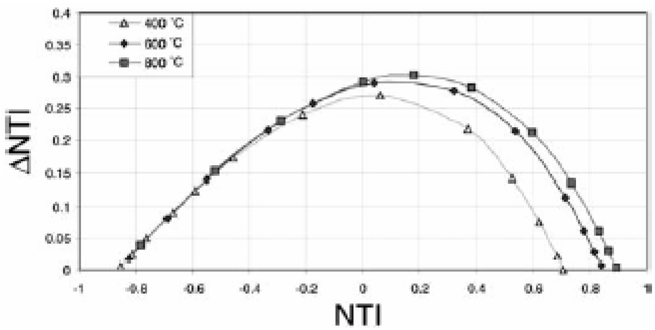

Figure 3 The relationship between normalized thermal index (NTI) of a spatially small thermal anomaly affecting a single pixel and the reduction in NTI (ΔNTI) if the same anomaly were shared equally between two adjacent pixels in the same scan line. Curves are shown for hot feature temperatures of 400, 600 and 800 °C, with an assumed background temperature of 25 °C.

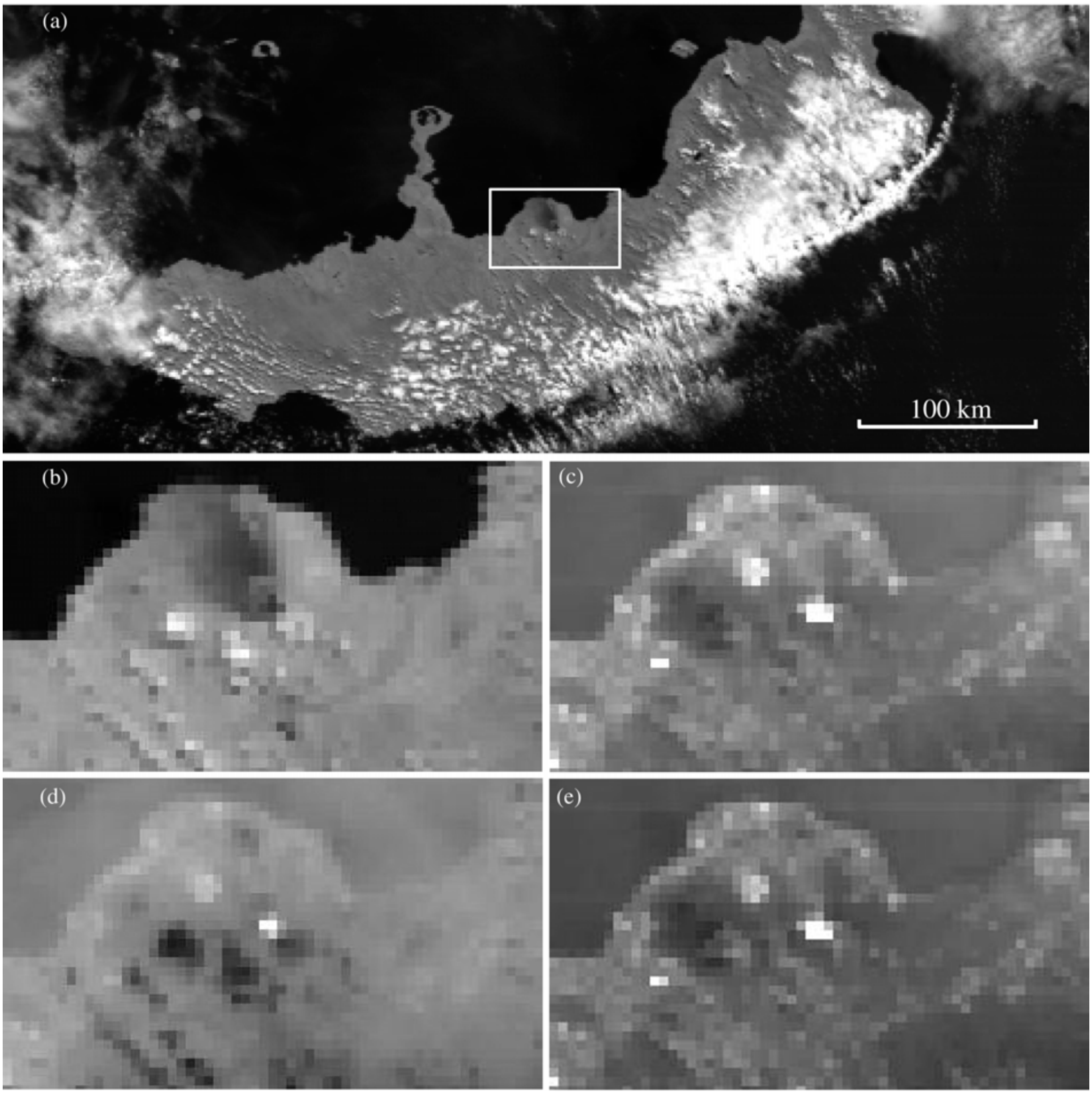

Figure 4 Day-time MODIS image recorded by the Terra satellite showing Pago on 15 August 2002. (a) MODIS channel 17 (reflected very-near infrared 890-920 nm) showing most of the

island of New Britain. Pago is in the centre. Below are four identically zoomed-in images 70 km wide of the immediate area centred on Pago, identified by the box in (a); (b) channel 17, (c) channel 22 (4 μm), (d) channel 32 (12 μm), (e) normalised thermal index (NTI, calculated from channels 22 and 32 as described in the text).

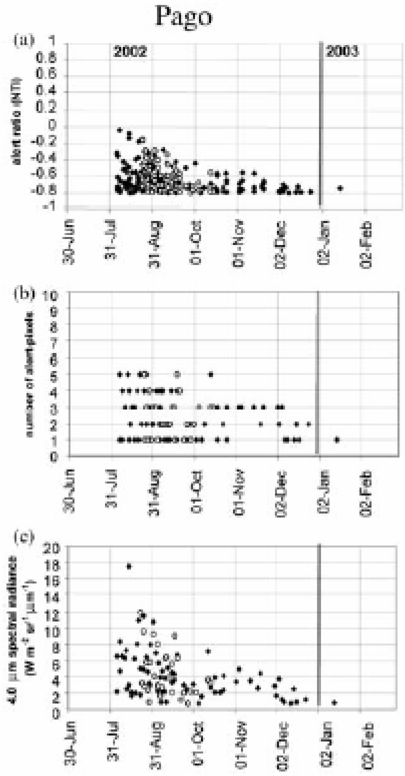

Figure 5 Time-series plots of MODIS thermal alerts for Pago. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 μm radiance for alert-pixels. No MODVOLC thermal alerts occurred January 2001-March 2003 outside the time-period shown here. Two satellites provided MODVOLC data during this eruption: Terra (solid symbols) and Aqua (open symbols).

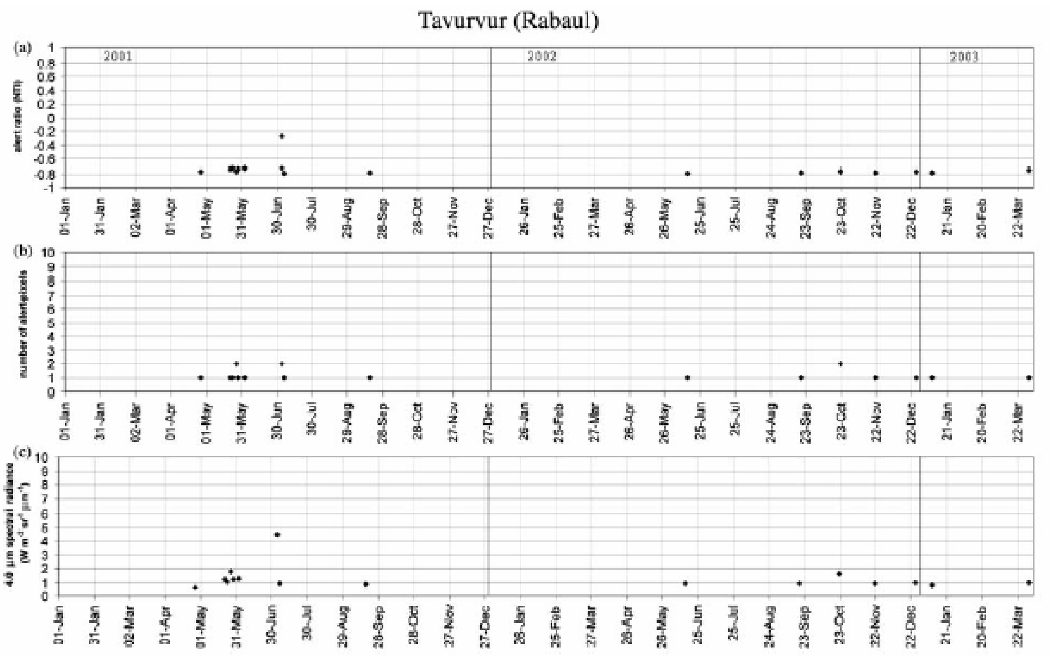

Figure 6 Time-series plots of MODVOLC thermal alerts for Rabaul (Tavurvur cone). (a) alert ratio (NTI). (b): number of alert pixels on each overpass. (c) summed 4.0 µm radiance for alert-pixels.

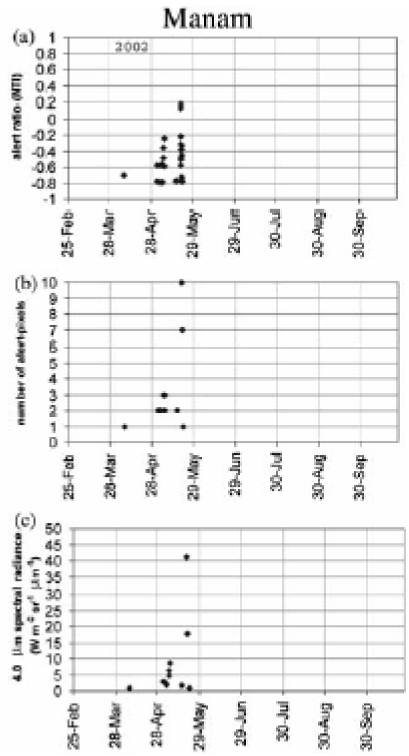

Figure 7 Time-series plots of MODVOLC thermal alerts for Manam. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 µm radiance for alert-pixels. No MODVOLC thermal alerts occurred January 2001-March 2003 outside the time-period shown here.

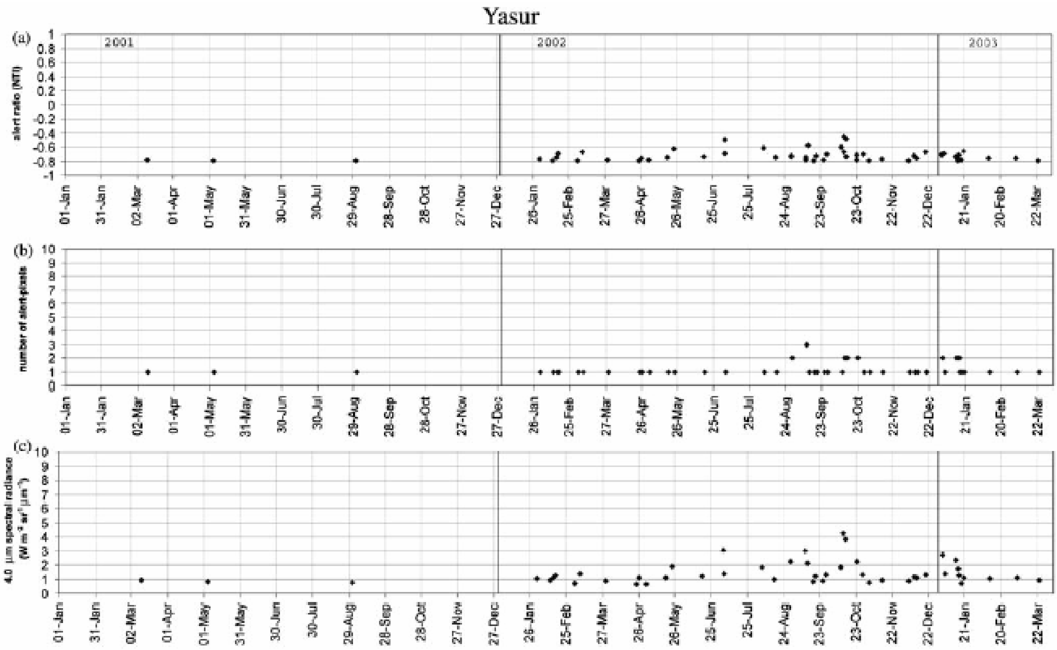

Figure 8 Time-series plots of MODVOLC thermal alerts for Yasur. (a): alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 μm radiance for alert-pixels.

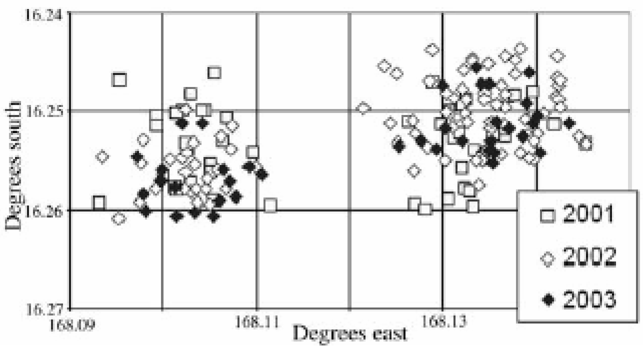

Figure 9 MODVOLC alert-pixel centre points for Ambrym. The two clusters correspond to the active lava lakes of Benbow (in the west) and Marum/Mbwelesu (in the east). Grid spacing is 0.01º, which is approximately 1 km.

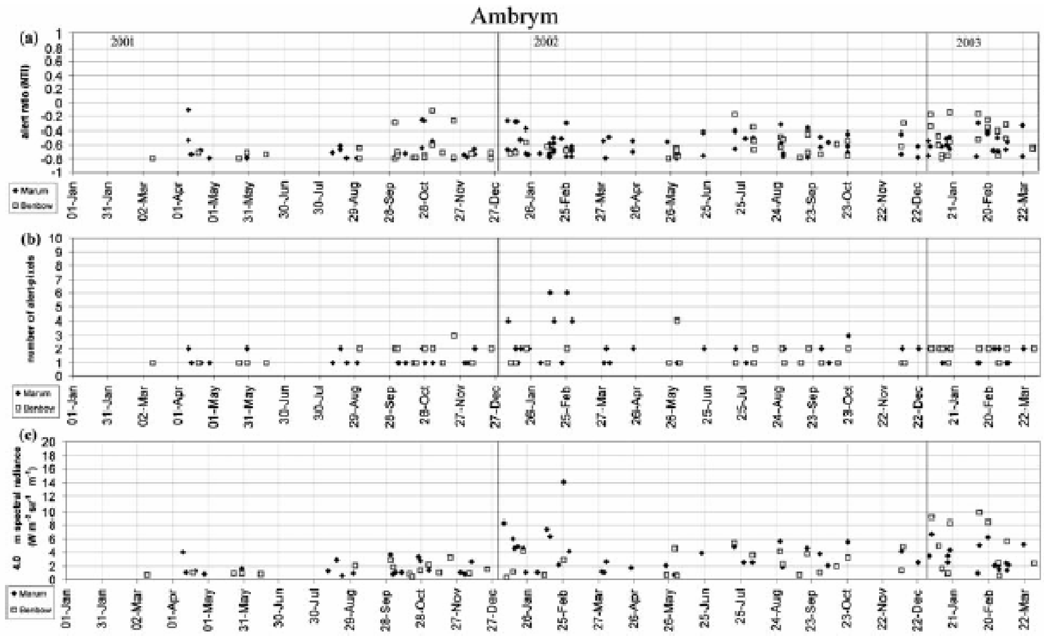

Figure 10 Time-series plots of MODVOLC thermal alerts for Ambrym, using different symbols to distinguish between pixels falling within each of the two centres: Benbow and Marum/Mbwelesu. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 µm radiance for alert-pixels.

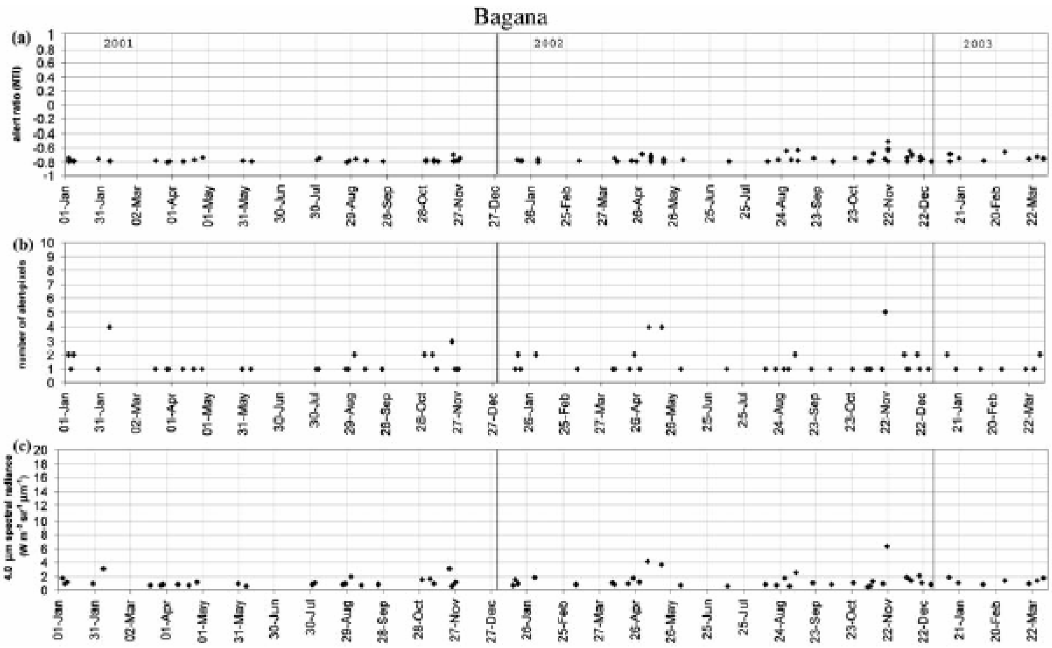

Figure 11 Time-series plots of MODVOLC thermal alerts for Bagana. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 µm radiance for alert-pixels.

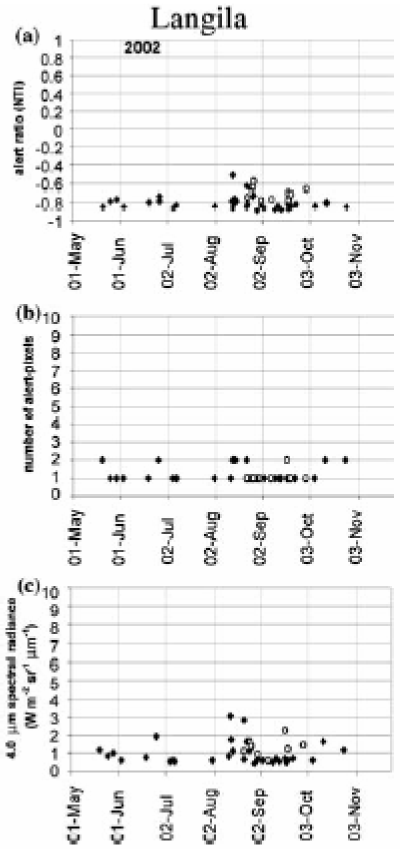

Figure 12 Time-series plots of MODVOLC thermal alerts for Langila. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 μm radiance for alert-pixels. In this example we have included Aqua thermal alerts (open symbols) and also Terra alerts that fell below the MODVOLC NTI thresholds (–0.800 by night and –0.600 by day).

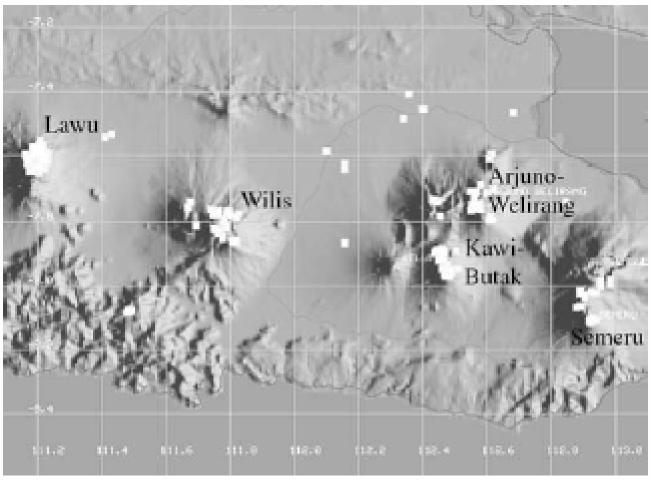

Figure 13 MODVOLC thermal alerts for a 2 degree-wide area of east-central Java during the month of October 2002, copied from the MODIS Thermal Alerts website. Grid squares are 0.2 degree, which is approximately 20 km. Volcanoes with thermal alerts are named in black, but except for the thermal alerts on Semeru (near the eastern edge) these are believed to represent fires rather than eruptive activity.

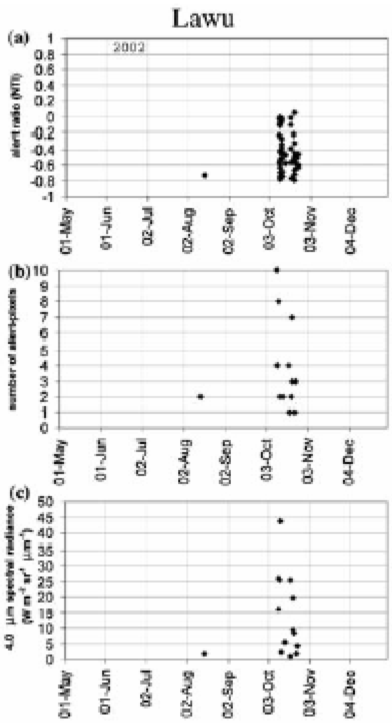

Figure 14 Time-series plots of MODVOLC thermal alerts for Lawu, which we believe to have been caused by fires. (a) alert ratio (NTI). (b) number of alert pixels on each overpass.(c) summed 4.0 µm radiance for alert-pixels.

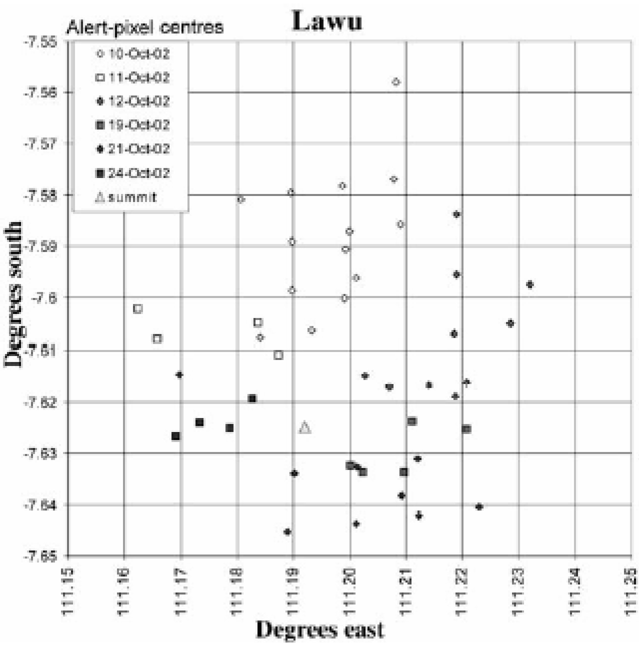

Figure 15 MODVOLC alert-pixel centre points for the Lawu thermal alerts of October 2002, showing their systematically evolving distribution relative to the summit location, which is consistent with fires rather than a volcanic origin. Axes are labelled in degrees south and east (0.01 of a degree is approximately 1 km).

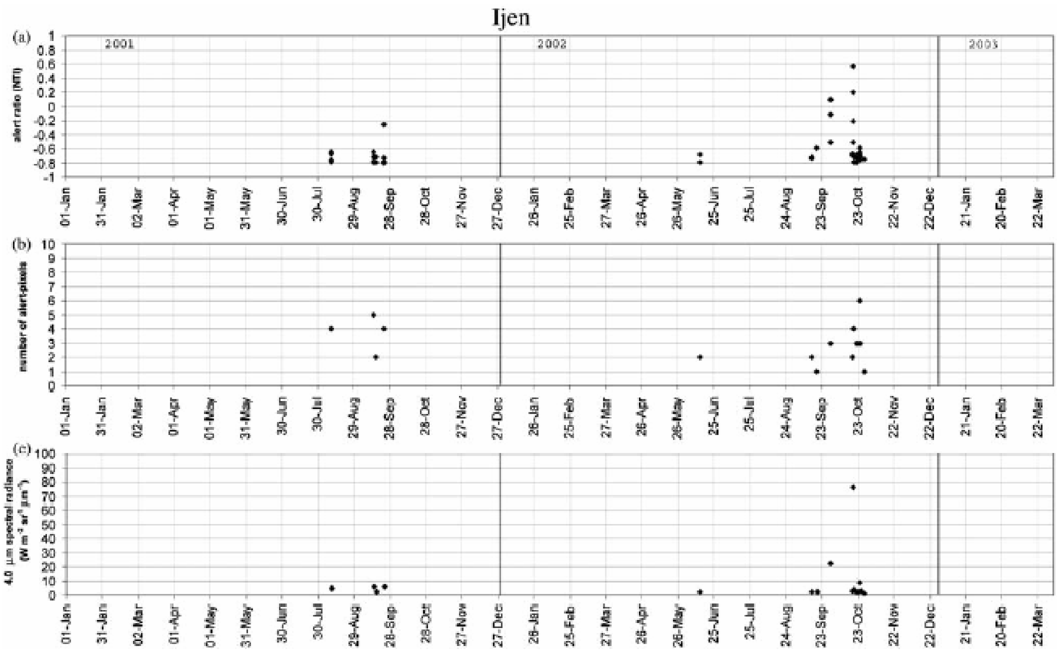

Figure 16 Time-series plots of MODIS thermal alerts Ijen, which we believe to have been caused by fires. In this example, we searched a greater area than the usual 10 km box in order to include the whole caldera. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 µm radiance for alert-pixels.

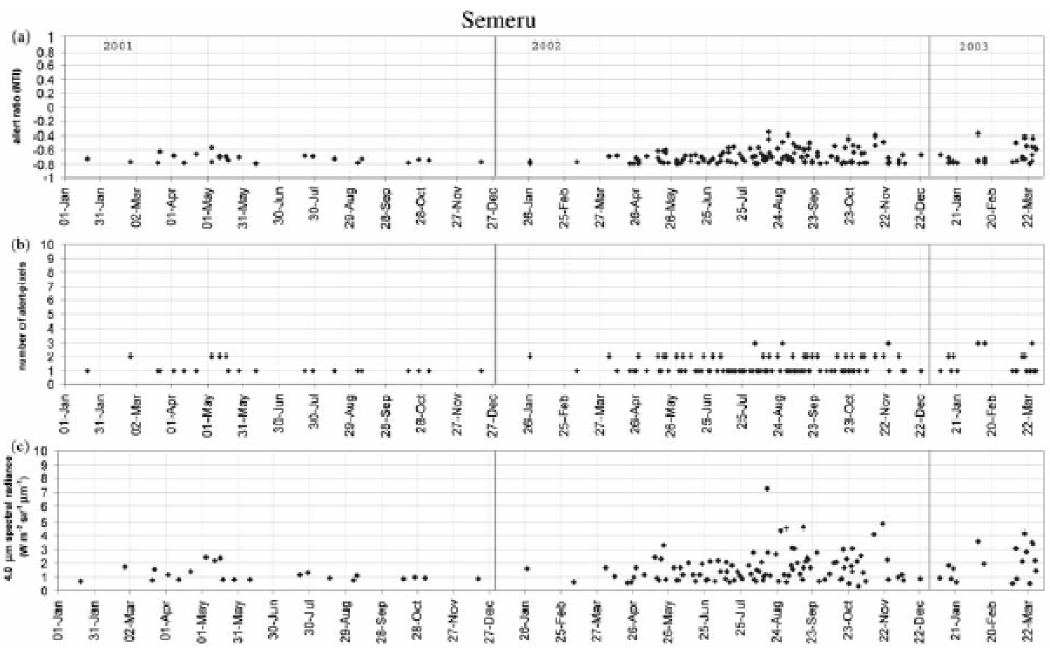

Figure 17 Time-series plots of MODIS thermal alerts for Semeru, which we believe to be volcanic in origin. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 µm radiance for alert-pixels.

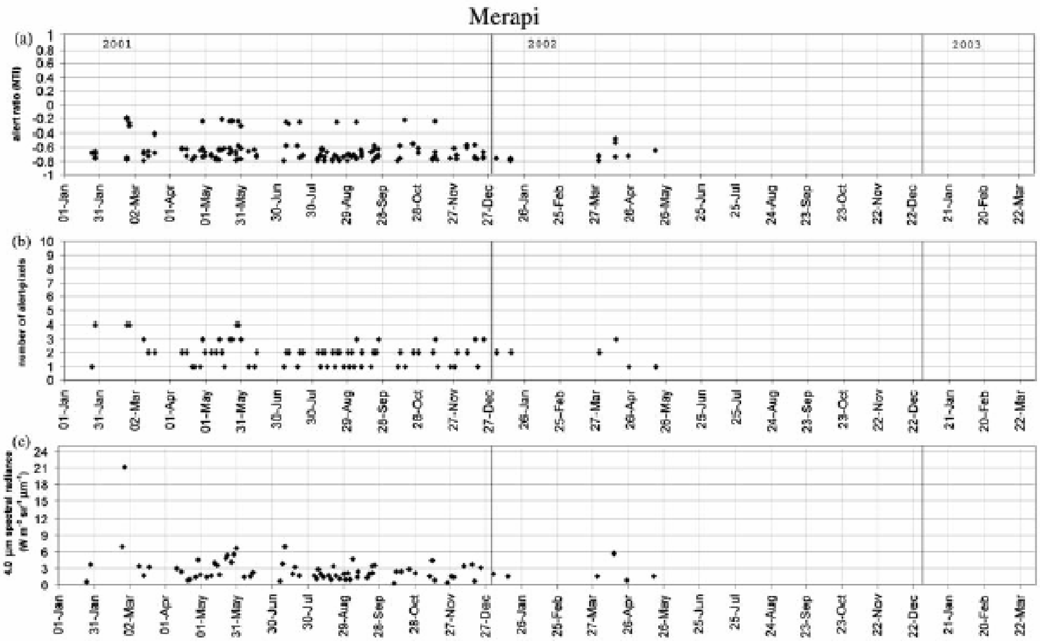

Figure 18 Time-series plots of MODIS thermal alerts for Merapi, which we believe to be volcanic in origin. (a) alert ratio (NTI). (b) number of alert pixels on each overpass. (c) summed 4.0 µm radiance for alert-pixels.

Table 1: MODVOLC thermal alerts for Melanesian volcanoes 1 January 2001 – 31 March 2003.
(PNG = Papua new Guinea)

Volcano name (location)	Dates of alerts	Type of activity
Ambrym (Vanuatu)	continual 10 Mar 2001-Mar 2003	Lava lakes
Bagana (Bouganville, PNG)	continual (entire period)	Lava dome
Langila (New Britain, PNG)	25 May-13 Oct 2002	Vent activity, lava dome/flows?
Lopevi (Vanuatu)	9-14 June 2001	Lava flows
Manam (offshore PNG)	7 Apr-21 May 2002	Strombolian activity
Pago (New Britain, PNG)	6 Aug 2002-15 Jan 2003	Lava flows
Rabaul (New Britain, PNG)	26 Apr-4 Jul 2001, 17 Sep 2001, 14 Jun 2002, Sep 2002- 31 Mar 2003	Explosive eruptions (Tavurvur come)
Tinakula (Santa Cruz Islands)	15 Jan, 6 Mar, 16 Apr 2001	Strombolian activity
Ulawun (New Britain, PNG)	26-28 Apr 2001	Strombolian eruption, pyroclastic flow, lava flow
Yasur (Vanuatu)	10 Mar, 4 Apr, 31 Aug 2001, continual 31 Jan 2002-Mar 2003	Explosive vent activity

Table 2: MODVOLC thermal alerts for Javanese volcanoes 1 January 2001 – 31 March 2003, including non-volcanic alerts that were triggered by fires rather than eruptions.

Volcano name	Dates of alerts	Cause
Agung (Bali)	23 Sep 2001, 12 Aug 2002, 5 Oct 2002	Fires
Arjuno-Welirang	13 Aug – 24 Oct 2002	Fires
Ijen	Aug – Sep 2001, May 2002, Sep – Oct 2002	Fires
Kawi-Butak	11–12 Aug 2002, 10 – 24 Oct 2002	Fires
Lawu	14 Aug- 21 Oct 2002	Fires
Lamongan	8 Aug – 13 Sept 2001 31 Aug – 26 Oct 2002	Fires
Krakatau	31 Jul –17 Sep 2002	Explosive eruptions
Merapi	24 Jan 2001– 14 Jan 2002, 30 Mar –17 May 2002	Lava dome, pyroclastic flows
Semeru	Jan 2001– Mar 2003	Explosive eruptions
Wilis	9 Aug – 26 Oct 2002	Fires